UNITED STATES PATENT APPLICATION

THREE-DIMENSIONAL PHOTONIC CRYSTAL WAVEGUIDE STRUCTURE AND METHOD

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ATTORNEY DOCKET 1303.034US1
MICRON 01-0828

THREE-DIMENSIONAL PHOTONIC CRYSTAL WAVEGUIDE STRUCTURE AND METHOD

Cross-reference to related applications

This patent application is related to U.S. Patent Application No. 09/861,770 filed on May 22, 2001, and entitled "Method of forming three-dimensional photonic band structures in solid materials," which Patent Application is incorporated herein by reference. This patent application is also related to U.S. Patent Application No. ___________, co-filed with the present application on January 17, 2002, and entitled "Three-dimensional complete bandgap photonic crystal formed by crystal modification," which Patent Application is incorporated herein by reference.

Field of the Invention

The present invention pertains to waveguides, and in particular to waveguide structures and methods employing photonic crystals.

Background of the Invention

The wave nature of electrons and the periodic lattice of atoms give rise to allowed energy bands and forbidden energy gaps for electrons in a solid. The forbidden gaps arise from the destructive interference of electrons for certain wavelengths and directions. If a forbidden gap exists for all possible directions, it is referred to as a complete bandgap. A semiconductor has a complete bandgap between the valence and conduction bands.

The optical analogy is the photonic crystal, where a periodic lattice of contrasting dielectric structures (i.e., different indices of refraction) provides the periodic potential for light that atoms do for electrons. Photonic crystals can be thought of as extensions of diffraction gratings (i.e., a one-dimensional photonic crystal) or naturally occurring crystals used in X-ray crystallography. Light interacting with a

diffraction grating or X-ray crystal interacts with the periodic structure and is redistributed into "allowed" and precluded from "forbidden" directions. The forbidden directions are the "photonic bandgaps" of the structure.

Photonic crystals can be designed with photonic bandgaps that prevent light of a certain wavelength and direction from propagating within the photonic crystal. If the photonic crystal does not allow light to propagate within a wavelength range for all polarizations and directions, it is said to have a "complete photonic bandgap." A necessary condition for a complete photonic bandgap is that the contrasting dielectric lattice be periodic in three dimensions (3D).

Research of photonic crystals and their behavior was prompted by the article by Yablonovitch, entitled "Inhibited spontaneous emission in solid-state physics and electronics," in *Phys. Rev. Lett.* 58, No. 20, 2059-2062 (1987). Based on theoretical considerations, a number of new optical devices, from better lasers to extremely miniaturized light switches and guides, have been suggested by workers in this relatively new field.

While photonic crystals offer a great deal of promise in fabricating new devices, fabricating such crystals with predetermined structures is daunting. The article by Yablonovitch et al., entitled "Photonic band structure: the face-centered-cubic case employing nonspherical atoms," in *Phys. Rev. Lett.* 67, No. 17, 2295-2298 (1991), describes the formation of the first artificial 3D photonic crystal by drilling an array of intersecting millimeter size holes in a dielectric material. This photonic crystal has a bandgap in the microwave range of the spectrum and is of limited practical interest.

Since the early pioneering work by Yablonovitch, a great deal of research has been devoted to the fabrication and study of photonic crystals in the infrared and visible. The article by Birner et al., entitled "Silicon-based photonic crystals," in *Adv. Mater.* 13, No. 6, March 16, 2001, describes fabricating two-dimensional (2D) and 3D photonic crystals. 2D photonic crystals have periodicity in two dimensions and are uniform in the third dimension and are much easier to fabricate than 3D photonic crystals. Although a 2D photonic crystal can not have a complete bandgap in the strictest sense, it can have a forbidden gap that exists for all directions and polarizations

of propagation precisely confined to the plane of periodicity. In this more limited sense, the forbidden gap is referred to as a "complete 2D bandgap."

One application for a 3D photonic crystal having a complete bandgap is to guide light. This can be accomplished by carving a path into such a photonic crystal to serve as an air-filled waveguide. Light that propagates in the air-filled waveguide at a frequency within the complete bandgap will be totally reflected by the photonic crystal and be totally confined to and directed along the waveguide. It should confine light around tight bends much better than conventional waveguides (e.g., optical fibers), where the guiding depends on the limited angular range of total internal reflection at the interface between the higher index core and the lower index cladding.

Much work has been done in the area of 2D photonic crystals. For example, the formation of a two-dimensional array of very small cylindrical holes with a diameter of about 1 micron fabricated in a silicon substrate by electrochemical etching is describe in the article by Birner et al., entitled "Microporous silicon: A two-dimensional photonic bandgap material suitable for the near-infrared spectral range," *Phys. Status Solids*, A 165, 111 (1998). As described in the article by Johnson et al., entitled "Guided modes in photonic crystal slabs," Phys. Rev. B, 60 5751 (1999), this technique has been further developed to form a triangular lattice of 0.36 micron holes on a 0.5 micron pitch to produce a 2D photonic crystal with a "complete 2D bandgap" at a free space wavelength of 1.25 micron.

The article by Loncar et al., entitled "Waveguiding in planar photonic crystals," *Appl. Phys. Lett.*, Vol. 77, No. 13, 25 September 2000, pp. 2813-2815, describes the fabrication of a 2D photonic crystal circuits designed and fabricated in silicon on silicon dioxide. The circuits include a planar waveguide that guides at 1.5 micron and utilizes a 2D photonic crystal consisting of a triangular lattice of cylindrical holes formed by chemically assisted ion-beam etching in silicon, as shown in Figure 2 of the article. A silicon slab waveguide is formed by omitting one row of cylindrical holes from the 2D photonic crystal. The top and bottom surfaces of the slab waveguide and the photonic crystal are in contact with air. The structure utilizes 2D lateral confinement by the 2D photonic crystal, while confinement in the vertical (i.e., third

dimension) is from conventional total internal reflection at the top and bottom Si/air interface. The article discusses propagation in straight sections and around 60° and 90° bends.

While 2D photonic crystal waveguides are useful for certain applications such as planar circuits and distributed feedback (DFB) lasers, there are a host of other applications (e.g., the formation of ultra-small optical and electro-optical integrated circuits and devices) that call for 3D photonic crystal waveguides. To date, however, readily forming 3D photonic crystals waveguides has proven difficult. This is particularly true where the desired bandgap wavelength is at the optical or infrared, since the dimensions of the lattice must be a fraction of the bandgap wavelength.

While some techniques have been developed for fabricating 3D photonic crystals, they involve extreme process conditions, such as forming individual dielectric layers and then stacking and bonding the layers to build the crystal. The formation of 3D waveguides in such crystals adds yet another level of complexity.

Accordingly, there is a need for an improved method of forming waveguides and waveguide-based devices from 3D photonic bandgap crystals.

Summary of the Invention

A method of forming a three-dimensional (3D) photonic crystal waveguide structure is shown, wherein the method includes forming in respective first and second substrates first and second 3D photonic crystal regions comprising a first and second periodic substantially identical arrays of voids that each form a complete bandgap. A channel is formed in at least one of the first and second 3D photonic crystal regions. The first and second photonic regions are then interfaced to form a 3D waveguide defined by the channel and a portion of the first or second 3D photonic crystal region that covers the channel. The periodic arrays of voids may be formed using surface transformation. Further, if the periodic array of voids is one that normally does not result in a complete bandgap, then the method may involve adding voids to the existing structure to create a modified structure having a complete bandgap.

In addition to the above, method, a waveguide structure formed in a 3D photonic crystal is shown. The waveguide structure includes a 3D photonic crystal comprising a periodic array of voids formed in a solid substrate so as to have a complete photonic bandgap. The voids can be any one of a number of shapes, including spherical. Further, the array of voids can be made up of any one of a number of unit cells, with the lattice constant of the cell selected to be a fraction of the wavelength associated with a desired complete photonic bandgap. A channel waveguide is formed in the 3D photonic crystal and is sized to transmit light of a wavelength corresponding to the complete photonic bandgap.

Further, a waveguide optical system that includes the waveguide structure described briefly above is shown. The 3D photonic crystal includes a periodic array of voids formed in a solid substrate. The periodic array is designed to form a complete photonic bandgap. A channel waveguide is formed in the 3D photonic crystal and is sized to transmit light of a wavelength corresponding to the complete photonic bandgap. A radiation source is operatively coupled to an input end of the channel waveguide to provide radiation to be transmitted down the waveguide. The waveguide optical system may further include a photodetector at an output end of the channel waveguide to receive and detect radiation that has traveled down the channel waveguide and that exits the output end of the channel waveguide. The photodetector produces an electronic signal that may be received by an electronic device and processed.

These and other embodiments, aspects, advantages, and features of the present invention will be set forth in part in the description which follows, and in part will become apparent to those skilled in the art by reference to the following description of the invention and referenced drawings or by practice of the invention. The aspects, advantages, and features of the invention are realized and attained by means of the instrumentalities, procedures, and combinations particularly pointed out in the appended claims.

Brief Description of the Drawings

Figure 1 illustrates fourteen representative unit cells with voids as "atoms," as examples of unit cells that can be used as a basis for forming the complete bandgap 3D photonic crystal waveguide structure of the present invention;

Figure 2 is a plot taken from the article by Ho et al. that graphs the gap/mid-gap ratio as a function of the filling ratio for a diamond crystal structure comprising air spheres formed in a solid dielectric substrate;

Figure 3A illustrates a diamond unit cell formed from spherical void "atoms" created in a solid substrate, where the "atoms" are linked by imaginary tetrahedral "bonds";

Figure 3B is a diagram representing the spherical void positions in the diamond unit cell of Figure 3A as projected on a cube face, with the fractions denoting the height above the base in lattice constant (a_0) units;

Figure 4 is a top-down perspective view of a substrate having formed therein cylindrical holes of a select length L, radius R and spacing S prior to forming spherical voids via surface transformation;

Figure 5A illustrates a modified diamond unit cell formed by modifying the diamond unit cell of Figure 3A by forming additional spherical voids halfway between the existing spherical voids along the tetrahedral bonds;

Figure 5B is the same plot as Figure 3B, but for the modified diamond unit cell of Figure 5A;

Figure 6A is a cross-sectional view of first and second substrates each having formed therein substantially identical 3D photonic crystal regions;

FIG 6B is a cross-sectional view of the first substrate of Figure 6A, with a channel formed in the surface of the 3D photonic crystal region;

Figure 6C is a top-down perspective view of the first substrate, with a channel having a bend formed in the 3D photonic crystal region;

Figure 6D is a top-down perspective view of the first substrate with a tapered channel formed in the 3D photonic crystal region;

Figure 6E is a cross-sectional view of the first and second substrates aligned and bonded to one another to form the channel waveguide;

Figure 6F is a cross-sectional diagram similar to Figure 6E, but wherein the second 3D photonic crystal region also has a channel;

Figure 6G is a cross-sectional view of the bonded substrates of Figure 6E, with the bottom surface of the second (top) substrate polished down to at or just above the 3D photonic crystal region of the second substrate; and

Figure 7 is a cross-sectional view of a 3D photonic crystal waveguide optical system that includes the 3D photonic crystal waveguide of Figure 6E.

In the Figures, the first digit of the reference number corresponds to the Figure number. Accordingly, like elements in different Figures have reference numbers that differ only in the first digit that identifies the Figure number.

Detailed Description of the Preferred Embodiments

In the following detailed description of the embodiments of the invention, reference is made to the accompanying drawings that form a part hereof, and in which is shown by way of illustration specific embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention, and it is to be understood that other embodiments may be utilized and that changes may be made without departing from the scope of the present invention. The following detailed description is, therefore, not to be taken in a limiting sense, and the scope of the present invention is defined only by the appended claims.

The term "substrate" as used in the following description includes any material, structure or combination of material/structure for which its optical, electronic, and acoustic properties, among others, can be modified by the formation or rearrangement of photonic energy bands in such material, structure, or combination thereof. Thus, the term "substrate" is understood as including, for example, linear and non-linear optical materials, metals, semiconductors and insulators/dielectrics, acoustic materials, magnetic materials, ferroelectric materials, piezoelectric materials, and superconducting materials, among others. In addition, the term "substrate" is understood as including

substrates formed on silicon, silicon-on-insulator, doped and undoped semiconductors, epitaxial layers of silicon supported by a base semiconductor foundation, and other semiconductor structures. Further, when reference is made to a semiconductor "substrate" in the following description, previous process steps may have been utilized to form regions or junctions in the base semiconductor structure or foundation.

Forming a 3D photonic crystal with complete bandgap

The present invention involves the formation of a complete bandgap 3D photonic crystal to create a fully confined 3D photonic bandgap waveguide structure. The complete bandgap 3D photonic crystal used to fabricate the waveguide structure is formed from a periodic array of voids created in a solid substrate. A preferred technique for creating such voids is called "surface transformation of empty spaces" (or "surface transformation," for short), which is described in detail in U.S. Patent Application Serial No. 09/861,770, filed on May 22, 2001, and entitled "Method of forming three-dimensional photonic band structures in solid materials," which Patent Application, as mentioned above, is incorporated herein by reference.

Using the surface transformation technique, a 3D photonic crystal of any lattice symmetry can be fabricated. Any one of a number of space group symmetries can be formed in a substrate of virtually any solid material by surface transformation, to control its optical and electromagnetic properties. The space group symmetries include a plurality of voids formed in the substrate by drilling holes to a predefined depth and at a predefined lattice position, and then heating the material at a temperature close to the melting point of the substrate material, to spontaneously form void patterns at the desired lattice position. The voids may have various geometries (e.g., spherical, cylindrical, plate-like, etc.) and may be formed at different periodicities and in a variety of space group symmetries using, for example, the representative unit cells of Figure 1, which are described by C. Kittel in *Introduction to Solid State Physics*, J. Wiley & Sons, 3d Ed., (1966).

As a general rule, the wavelength of the photonic bandgap is about twice the period (i.e., lattice constant a_0) of the photonic crystal. Thus, to achieve a bandgap for

a desired wavelength (e.g., x-ray, ultraviolet, visible, infrared, microwave, etc.), the lattice constant a_0 should be a fraction of the desired wavelength. The wavelength and width of the photonic bandgap also depend on the filling ratio, which is the ratio of the volume of the voids in the unit cell to the total volume of the unit cell.

According to the teaching of the present invention, by properly selecting the lattice constant a_0 and the "atom" (i.e., void) shape and size, a variety of 3D photonic crystals and thus 3D photonic crystal waveguide structures can be produced for the wavelength region of interest. The lower bound of the photonic bandgap wavelength is determined mainly by the smallest lattice constant a_0 and voids that can be formed in the particular substrate.

Waveguide structure with modified 3D photonic crystal

As mentioned above, the 3D photonic crystal waveguide structure of the present invention requires the formation of a complete bandgap 3D photonic crystal. However, certain 3D photonic crystals formed with certain space group symmetries and voids of a given size and/or shape may not provide the necessary complete photonic bandgap at one filling ratio but may do so at another. Thus, the present invention includes a method of forming a waveguide structure using a 3D photonic crystal modified to form a complete bandgap. A technique for forming a modified 3D photonic crystal structure is described in U.S. Patent Application No. __________, filed on ______ and entitled "Three-dimensional complete photonic bandgap crystal formed by crystal modification," which Patent Application is incorporated by reference herein.

Ho et al., in their article entitled "Existence of a photonic gap in periodic dielectric structures," *Phys. Rev. Lett.*, Vol. 65, No. 25, 17 Dec. 1990, pp. 3152-3155, which article is incorporated by reference herein, have calculated the photonic band structure of the diamond lattice for air spheres (i.e., spherical voids) of various sizes in a dielectric background. Ho et al. have identified the conditions under which a complete bandgap exists for a diamond lattice of spherical voids.

Figure 2 is adapted from the article by Ho (Figure 3(a) therein), and plots the "gap/mid-gap ratio" versus the filling ratio for air spheres formed in a solid substrate.

The gap/mid-gap ratio is the ratio of the size of the calculated bandgap (in units of frequency) of the diamond crystal normalized to the mid-gap frequency.

From Figure 2, it can be seen that a filling ratio of about 0.35 or greater is required to achieve a complete bandgap. Further, the gap/mid-gap ratio grows until a filling ratio of about 0.8 is reached, at which point the gap/mid-gap ratio decreases rapidly.

Figures 3A and 3B illustrate a 3D photonic diamond lattice crystal 310 of spherical voids 320 with a lattice constant a_0 formed in a substrate 324. Spherical voids 320 are connected by imaginary tetrahedral "bonds" 330. It is assumed below for the sake of illustration that substrate 324 is silicon (optical index, $n = 3.6$), with the x and y axes in the plane of the substrate and the z-axis normal to the substrate plane. It is further assumed, as an example embodiment, that spherical voids 320 are formed by surface transformation.

As illustrated in Figure 4, surface transformation involves drilling into substrate 424 a defined set of cylindrical holes 436 having a specific radius R, depth L and separation S (e.g., equal to lattice constant a_0), and then annealing the substrate. It will be understood that the method described below can be applied to forming complete photonic bandgaps in other high index ($n > 2$) substrates such as GaAs, InP, etc., by modifying the annealing conditions.

For simplicity, the formation of one unit cell in (x,y) and N unit cells in the Z-direction is described. To form additional unit cells in the (x,y) plane, repeated translation of the hole pattern, modulo a_0, in the x and y directions is all that is required.

To create spherical voids with a lattice periodicity a_0 in the z-direction into the substrate requires that the radius of the cylindrical holes must be:

$R = a_0/8.89 \sim 0.11\ a_0$.

After surface transformation, the radius R_S of each spherical void 20 is:

$R_S = (1.88/8.99)a_0 \sim 0.212\ a_0$

The depth L of the initial cylindrical holes required to form by surface transformation each unit cell and the spherical void lattice sites at (x,y,z) for the N unit cells in the z-direction are:

(a) For unit cell sites (1,0,1) and (0,1,1):
L_1= (N) a_0 = (N) 8.89 R

(b) For (3/4,1/4,3/4) and (1/4,3/4,3/4):
$L_{3/4}$= (N+1/4) a_0

(c) For (1/2,0,1/2) , (0,1/2,1/2) , (1,1/2,1/2) and (1/2,1,1/2)
$L_{1/2}$=(N +1/2) a_0

The two lattice points (1,1/2,1/2) and (1/2,1,1/2) are actually in the next adjacent x-translated and y-translated unit cells, respectively. They are given to be consistent with Figures 3A and 3B, but are omitted when translating the unit cell in the x and y direction modulo a_0.

(d) For (1/4,1/4,1/4) and (3/4,3/4,1/4):
$L_{1/4}$= (N+3/4) a_0

(e) For (0,0,0), (1/2,1/2,0) and (1,1,0):
L_0= (N+1) a_0

During annealing (e.g., at 1100° C in a 10 torr atmosphere of hydrogen), spherical voids 320 form in silicon substrate 324 at each of the lattice sites in the vertically stacked N unit cells of diamond lattice 310, as depicted in Figure 3A.

Since the nearest neighbors in diamond lattice 310 are 0.433 a_0 distant along the directions of tetrahedral bonds 330 and the spherical void radius R_S is 0.21 a_0, the surface transformation formed diamond lattice has a filling ratio of only 0.32.

With reference again to the plot of Figure 2, it can be seen that the filling ratio of 0.32 is not sufficient to produce a complete bandgap (i.e., at a filling ratio of 0.32, the gap size is zero). However, if the fill ratio can be increased to about 0.35 or greater, then a complete bandgap can be achieved.

With reference now to Figures 5A and 5B, the diamond crystal 310 of Figure 3A is modified to include additional spherical voids 540 of radius $0.212a_0$ at a point halfway along each of tetrahedral bond 530. Spherical voids 540 do not alter the diamond symmetry, yet they increase the filling ratio to 0.48, resulting in a complete bandgap with a gap/mid-gap ratio of about 0.1. The crystal 510 shown in Figures 5A and 5B is referred to herein as a "modified diamond crystal."

The depth L of the initial cylindrical hole required to form by surface transformation spherical voids 520 and 540 at each unit cell lattice location at (x,y,z) for the N modified unit cells in the z-direction are:

(A) For lattice sites (1,0,1) and (0,1,1)
$L_1 = (N)\, a_0$

(B) For (7/8,1/8,7/8), (5/8,3/8,7/8), (3/8,5/8,7/8) and (1/8,7/8,7/8)
$L_{7/8} = (N + 1/8)\, a_0$

(C) For (3/4,1/4,3/4) and (1/4,3/4,3/4)
$L_{3/4} = (N+1/4)\, a_0$

(D) For (5/8,1/8,5/8), (7/8,3/8,5/8), (1/8,5/8,5/8) and (3/8,7/8,5/8)
$L_{5/8} = (N+3/8)\, a_0$

(E) For (1/2,0,1/2), (0,1/2,1/2), (1,1/2,1/2), and (1/2,1,1/2)
$L_{1/2} = (N+1/2)\, a_0$

As before, lattice sites (1,1/2,1/2) and (1/2,1,1/2) are actually in the next unit adjacent x-translated and y-translated unit cells respectively. They are given to be consistent with Figures 5A and 5B but need to be omitted when translating the unit cell in the x and y direction modulo a_0.

(F) For (3/8,1/8,3/8), (1/8,3/8,3/8), (7/8,5/8,3/8) and (5/8,7/8,3/8)
$L_{3/8} = (N + 5/8)\, a_0$

(G) For (1/4,1/4,1/4), and (3/4,3/4,1/4)

$L_{1/4} = (N+3/4)\ a_0$

(H) For (1/8,1/8,1/8), (3/8,3/8,1/8), (5/8,5/8,1/8) and (7/8,7/8,1/8)

$L_{1/8} = (N+ 7/8)\ a_0$

(I) For (0,0,0),(1/2,1/2,0) and (1,1,0)

$L_0 = (N+1)\ a_0$

Annealing (e.g., at 1100° C and in a 10 torr hydrogen atmosphere) substrate 524 with the above-defined pattern of cylindrical holes produces spherical voids 520 at the apexes of the tetrahedral bonds 530 and spherical voids 540 halfway between spherical voids 520 along the tetrahedral bonds 530 in the vertically stacked N unit cells of the modified diamond lattice, as depicted in Figures 5A and 5B.

The annealing time required to form N (z-stacked) unit cells can be estimated using, for example, the approach described in the paper by Matsutake and Ushiku, presented in the Extended Abstracts of the "2000 International Conference on Solid State Devices and Materials," Tokyo, Japan, pp. 198-199 (2000). For $a_0 \sim 1$ micron and hence $R \sim 0.1$ micron, the annealing time (in seconds) for formation of N (z-stacked) unit cells is estimated to be $\sim N \times 40$.

Although the formation of a complete bandgap 3D crystal lattice from incomplete bandgap crystal lattice has been described in connection with modifying a diamond lattice of spherical voids formed in a silicon substrate, the method applies generally to modifying any incomplete bandgap crystal lattice. The method described in article by Ho et al. can be employed to determine whether a particular crystal structure will have a complete bandgap and if not, if the crystal structure can be modified to produce a complete bandgap. Alternatively, whether a particular crystal structure will yield a complete bandgap, or whether a particular crystal structure can be modified to achieve a complete bandgap can be determined empirically.

3D photonic crystal waveguide formation

Methods of forming a fully confined 3D photonic bandgap waveguide structure are now described with reference to Figures 6A through 6G.

In Figure 6A, first and second substrates 600 and 604 with respective top surfaces 610 and 612 and respective bottom surfaces 618 and 620 are provided. A first 3D photonic crystal region 630 with an upper surface 632 and a complete bandgap is formed in first substrate 600 to a depth of at least 10 to 15 lattice constants a_0 and a width of at least 20 to 30 lattice constants. A second 3D photonic crystal region 640 with an upper surface 642 and a complete bandgap is formed in second substrate 604 Second 3D photonic crystal region 640 is preferably identical (or substantially identical, to within about $0.1a_0$) to first 3D photonic crystal region 630.

In an example embodiment, first and second 3D photonic crystal regions 630 and 640 are formed by surface transformation. Further in an example embodiment, first and second 3D photonic crystal regions are formed to have modified crystal structures with complete bandgaps, as discussed above in connection with the example of a modified diamond crystal structure. Generally, first and second 3D photonic crystal regions can have any arrangement of voids that provides a complete bandgap.

In an example embodiment, top surface 610 of substrate 600 includes alignment marks 650 adjacent first 3D photonic crystal region 630, and top surface 612 of substrate 604 includes alignment marks 656 adjacent second 3D photonic crystal region 640. Alignment marks 650 and 656 are designed to facilitate the mutual alignment of 3D photonic crystal regions 630 and 640, as described below.

In Figure 6B, a channel 660 is formed in upper surface 632 of 3D photonic crystal region 630 by removing a number (e.g., 1 to 4) unit cells in the horizontal (Y-direction) and a number (e.g., 1 to 4) unit cells in the vertical (Z-direction). The precise number of unit cells removed depends on the lattice constant and the wavelength of light to be guided. Generally speaking, channel 660 is sized to transmit light of a wavelength corresponding to the complete bandgap of the 3D photonic crystal regions 630 and 640. Any one of a number of standard lithographic techniques, such as etching, can be used to form channel 660. Channel 660 includes a lower wall 662 and

opposing sidewalls 666. In an example embodiment, channel 660 has a rectangular cross-section, as shown. In another example embodiment illustrated in Figure 6C, channel 660 includes a bend 670. Though channel 660 is shown to be rectangular in cross-section, other shapes, including a tapered channel 672 as shown in Figure 6D, can be formed.

In Figure 6E, substrates 600 and 604 are placed so that their top surfaces 610 and 612 are confronting. 3D photonic crystal regions 630 and 640 are then aligned with one another (e.g., through the use of alignment marks 650 and 656) and top surfaces 610 and 612 are brought into contact and bonded together using standard substrate bonding techniques. The bonded structure creates, in effect, a single 3D photonic crystal with a 3D channel waveguide 680 defined by lower wall 662, opposing sidewalls 666 of channel 660, and the portion of upper surface 642 of second 3D photonic crystal region 640 covering the channel.

In Figure 6F, an alternative example embodiment is illustrated wherein a rectangular channel 688 having the same width as channel 660 is formed in region 640, so that a channel waveguide 690 is formed from the channels in each of 3D photonic crystal regions 630 and 640.

In Figure 6G, bottom surface 620 of substrate 604 and/or bottom surface 618 of substrate 600 is/are optionally polished down close to 3D photonic crystal region 640 and/or 3D photonic crystal region 630. In some cases, it might be desirable to polish to the top of one or both of 3D photonic crystal regions 640 and 630, or even into one or both of the 3D photonic crystal regions down to near waveguide 680.

3D photonic crystal waveguide optical system

The present invention includes a 3D photonic crystal waveguide optical system 701 formed using the 3D photonic crystal waveguide described immediately above and shown, for example, in Figures 6E and 6G.

With reference to Figure 7, waveguide optical system 701 includes a radiation source 703 operatively coupled to an input end 707 of 3D photonic waveguide 780 so that radiation 721 emitted from the radiation source is transmitted down the waveguide.

Radiation 721 has a wavelength within the photonic bandgap of 3D photonic crystal regions 730 and 740 that define waveguide 780. In an example embodiment, radiation source 703 is a laser, such as a diode laser or vertical cavity surface emitting laser (VCSEL).

Radiation 721 is confined in 3D over the entire range of possible propagation angles due to the omnidirectional reflection by each complete bandgap crystal surface e.g., lower channel wall 732, the channel sidewalls (not shown; see 666, FIG. 6G), and upper surface 742 defining waveguide 780. Because waveguide 780 may contain either air, another gas (e.g., nitrogen) or a vacuum, the waveguide is expected to have a transmission loss comparable to or better than today's low loss fibers (0.3 dB per kilometer) used for long-distance optical communication. Also, bending losses from bends (e.g., bend 670, FIG. 6C) should be remarkably low as compared to conventional waveguides because the reflection mechanism of complete bandgap photonic crystals is not sensitive to incident angle. This allows for waveguide 780 to have bends of up to 90 degrees, providing more design latitude in fabricating waveguide-based integrated optical systems such as couplers, Y-junctions, add-drop multiplexers, and the like.

With continuing reference to Figure 7, a photodetector 777 is operatively coupled to an output end 783 of waveguide 780 to receive and detect radiation 721 having traveled down the waveguide, and to generate an electrical signal (i.e., a photocurrent) 787 in response thereto. Connected to photodetector 777 is an electronic system 791 operable to receive and process electrical signal 787.

Conclusion

The present invention is a 3D photonic crystal waveguide structure and methods of forming same. The 3D photonic crystal used in the present invention comprises a periodic array of voids, which in an example embodiment, are formed using the surface transformation technique. Further, in forming the waveguide structure, two 3D photonic crystal regions are interfaced and bonded to form a single 3D photonic crystal. This allows for the waveguide structure to be readily fabricated by forming a channel in at least one of the 3D photonic crystal regions.

The methods of the present invention also allows for a wide variety of different 3D photonic crystal waveguides to be formed, with complete bandgaps at wavelengths ranging from the very small (e.g., ultraviolet and below) to the relatively large (infrared and above). Further, the present invention provides for utilizing a 3D photonic crystal structure modified to have a complete bandgap to form the 3D waveguide structure.

While the present invention has been described in connection with preferred embodiments, it will be understood that it is not so limited. On the contrary, it is intended to cover all alternatives, modifications and equivalents as may be included within the spirit and scope of the invention as defined in the appended claims.